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Emerging Techniques for Vicarious Calibration of Visible Through Short Wave Infrared Remote Sensing Systems

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Contributors

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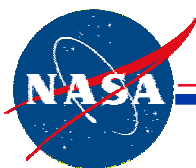
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 - Tom Stanley
 - Troy Frisbie



Topics

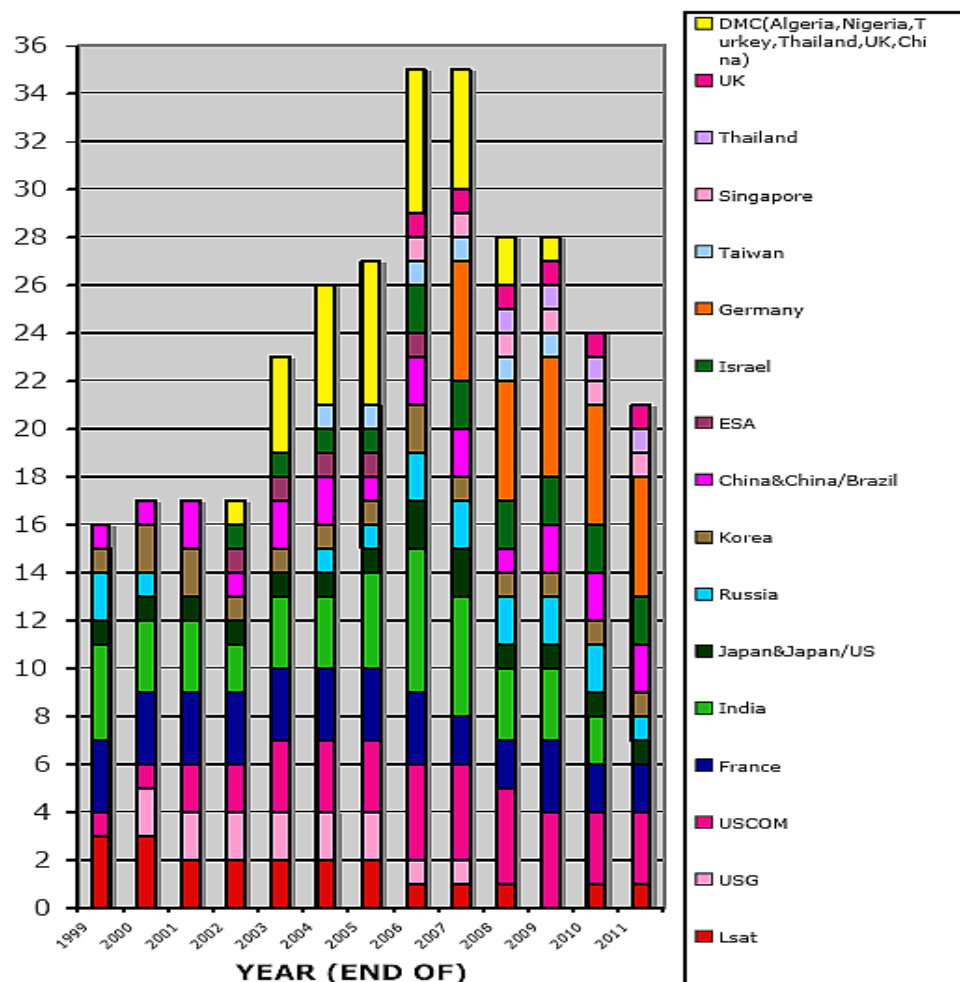
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- Background
- Emerging Cal/Val needs
- Current vicarious calibration techniques
- Radiative transfer validation
- Alternative sun photometers
- LED-based calibration sources
- Summary



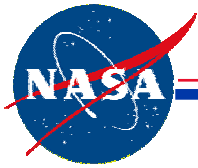
Background

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- Over the next several years, more than 50 optical satellite imaging systems with 39 m or better resolution could be in orbit
 - 13 countries presently have imaging satellites in orbit
 - 20 countries will have imaging satellites in orbit by 2010
 - 30 imaging systems are in orbit
 - 25 imaging systems are planned by 2010
- These figures do not include the large number of advanced airborne multispectral imaging systems

Source: Stoney, W.E., 2006. *Guide to Land Imaging Satellites*. February 2, p. 10. http://www.asprs.org/news/satellites/ASPRS_DATABASE_020206.pdf



Issues

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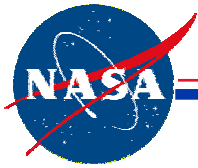
- The scientific community needs high-quality and well-understood image products
 - Geopositionally and radiometrically accurate products
 - Well-understood spatial resolution
- Insight into the system construction, calibration, and performance will be limited in many cases
- Most systems will not have any onboard radiometric calibration
- Cal/Val (vicarious calibration) will be essential
 - Multiple approaches are desirable
 - Ground-based reflectance radiometric methods have the greatest utility because all systems image the ground



Issues (Cont.)

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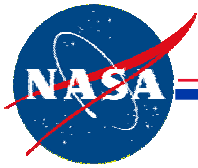
- Ground-based radiometric calibrations currently require teams of trained staff taking coincident data at the time of overpass and analysts to estimate Top-of-the-Atmosphere (TOA) radiance
 - Costly
 - Significant coordination is required between the imagery provider and the calibration team
 - A variety of sites is needed
- Improved TOA radiance estimates are needed
 - Level of confidence in ground truth data is limited because robust Cal/Val is lacking
 - Level of confidence in radiative transfer modeling is limited because independent validation methods are lacking



Issues (Cont.)

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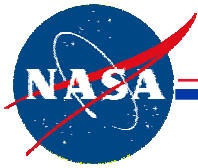
- Robust automated systems are clearly needed to effectively calibrate and validate products from such a large number of systems
 - Several years away
 - Concerted, well-funded projects will need to be established



Ground-based Radiometric Cal/Val Needs

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- Near term
 - Increased confidence in ground truth and modeling through multiple independent methods for validation
 - Measurement techniques that reduce or at least do not increase staff
 - Simpler and more accurate calibration approaches
- Mid term
 - Development of techniques that are compatible with autonomous measurements
- Long term
 - Fully autonomous vicarious calibration techniques and sites



SSC Near Term Cal/Val Development Goals

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- Improved accuracy and higher confidence in TOA radiance estimates
 - Radiative transfer modeling validation
 - Alternative sun photometer calibration and validation
 - Low-cost, simple, in-field, NIST-traceable radiometric calibration source

Autonomous approaches will evolve from improved, traditional, labor-intensive, radiometric calibrations

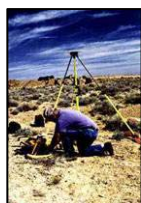


Stennis Verification & Validation (V&V) Site

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Sandmeier Field Goniometer for Bi-directional Reflectance Measurement



GPS, Spectroradiometer, and Upper Atmosphere Surveys



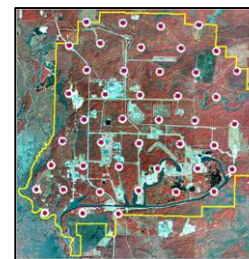
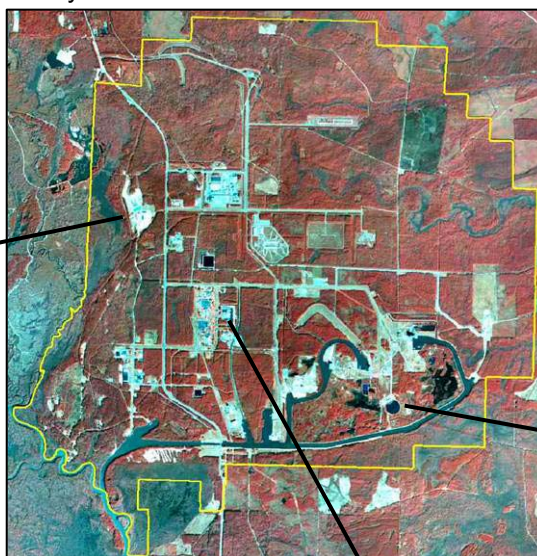
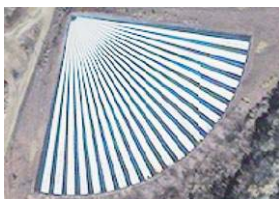
Radiometric Tarps



Total Sky Imagers



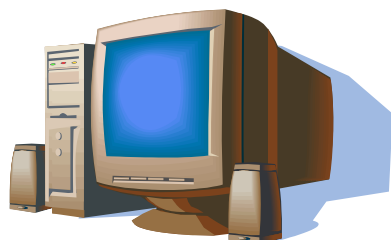
Two 20 x 40 m Edge Targets and 130 m Radial Target



Network of Ground Control Points



Water Surface Temperature Sensor



Atmospheric Modeling (MODTRAN)

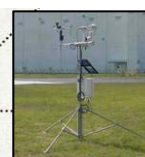
Total Sky Imager



Multifilter Shadowband Radiometer



Atmospheric Measurement System

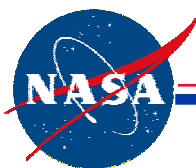


Surface Meteorology Stations



NASA GSFC AERONET Node

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First-Generation Reflectance-Based Vicarious Calibration

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	Measurements for Radiative Transfer Modeling							
	Target Reflectance	Background Reflectance	Aerosol Optical Depth	Molecular Scattering Optical Depth	Aerosol Asymmetry Factor	H ₂ O	O ₃	Radiative Transfer Validation
ASR Sun Photometer			X	X		X	X	
MFRSR Sun Photometer			X	X	X	X	X	
ASD and Calibrated Panel (Reflectance Only)	X							
Reflectance Targets	X	X Empirical Line Method						

Radiative transfer modeling accuracy relies solely on code inputs, code accuracy, and selection of good sites (Traditional Approach)

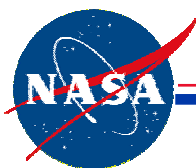


Second-generation Reflectance-based Vicarious Calibration

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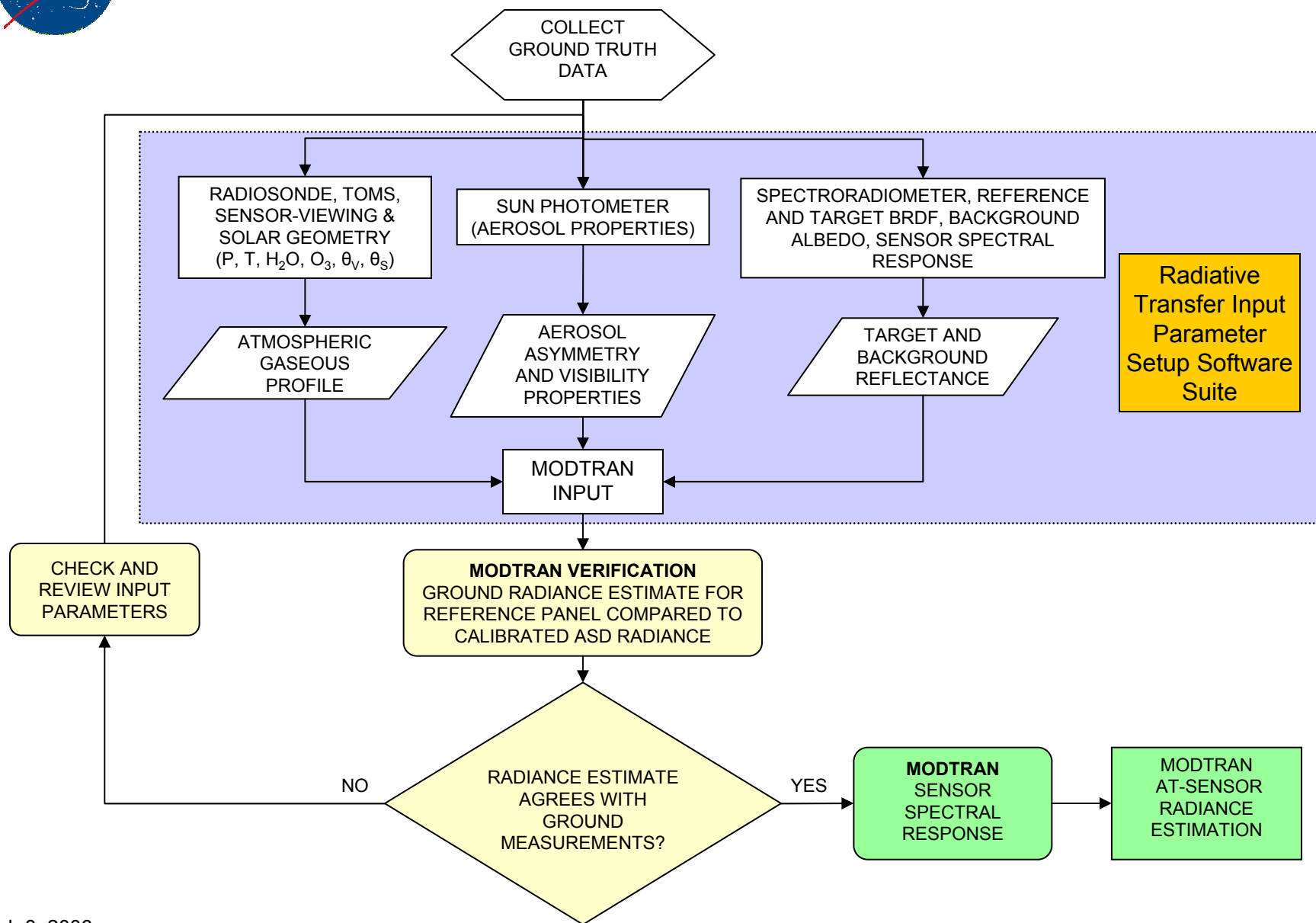
	Measurements for Radiative Transfer Modeling							
	Target Reflectance	Background Reflectance	Aerosol Optical Depth	Molecular Scattering Optical Depth	Aerosol Asymmetry Factor	H ₂ O	O ₃	Radiative Transfer Validation
ASR Sun Photometer			X	X		X	X	
MFRSR Sun Photometer			X	X	X	X	X	
Radiometrically Calibrated ASD & Calibrated Panel	X							X
Reflectance Targets		X Empirical Line Method						
Satellite H ₂ O & O ₃						X	X	

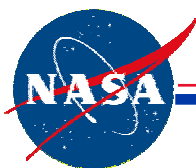
Radiometrically calibrated spectroradiometer panel radiance measurements allow for radiative transfer modeling validation



Typical Radiometric Vicarious Calibration

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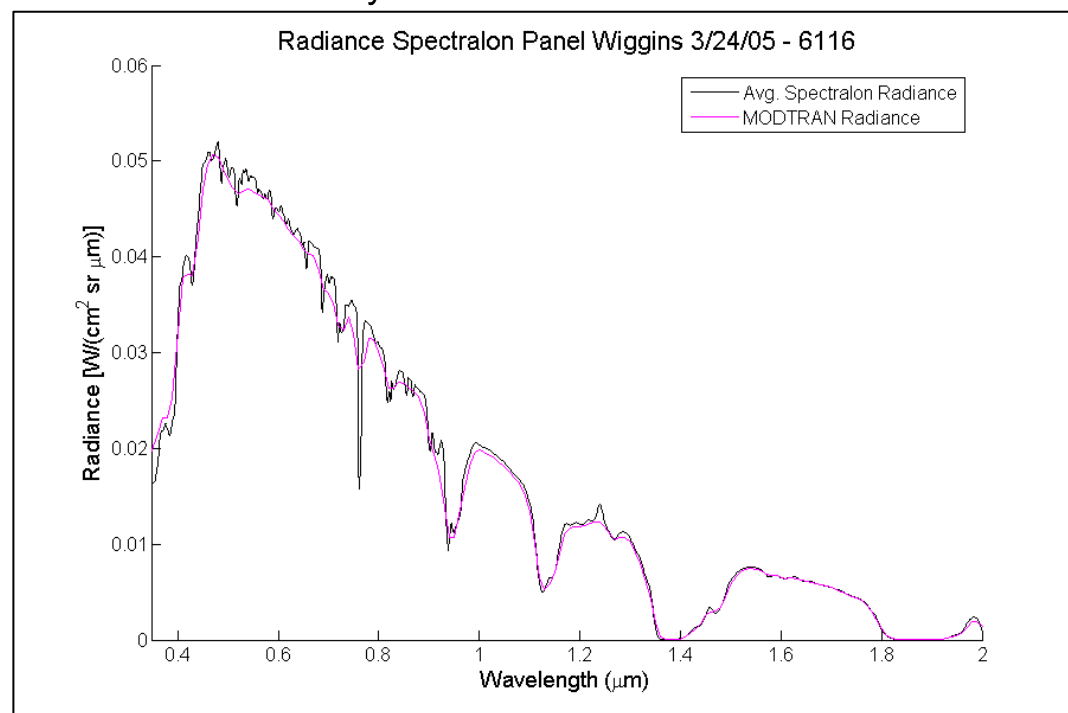




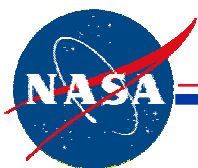
Radiative Transfer Validation

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- Verify parameters used to generate MODTRAN at-sensor radiance estimate
 - Measure the radiance off a Spectralon® panel with a well-calibrated spectroradiometer
 - Use ground truth data and geometry that models an ASD FieldSpec® FR (Full Range) spectroradiometer measuring a 99% reflectance Spectralon panel as input to MODTRAN to predict radiance
 - Compare MODTRAN-calculated radiance to actual radiance measured from Spectralon panel to verify the atmospheric model
 - After panel BRDF correction and radiometric calibration with NIST-calibrated integrating sphere, the expected panel radiance measurement uncertainty is ~2-3%



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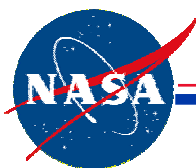
Calibration and Characterization of ASD FieldSpec Spectroradiometers

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- NASA SSC maintains four ASD FieldSpec FR spectroradiometers
 - Laboratory transfer radiometers
 - Ground surface reflectance for V&V field collection activities
- Radiometric Calibration
 - NIST-calibrated integrating sphere serves as source with known spectral radiance
- Spectral Calibration
 - Laser and pen lamp illumination of integrating sphere
- Environmental Testing
 - Temperature stability tests performed in environmental chamber



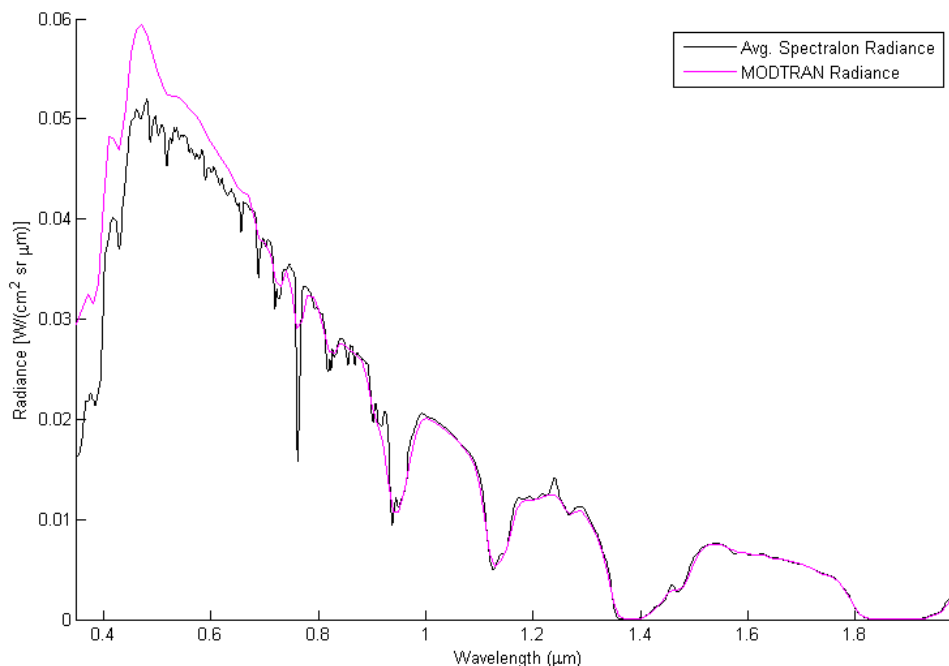
Environmental Chamber with ASD



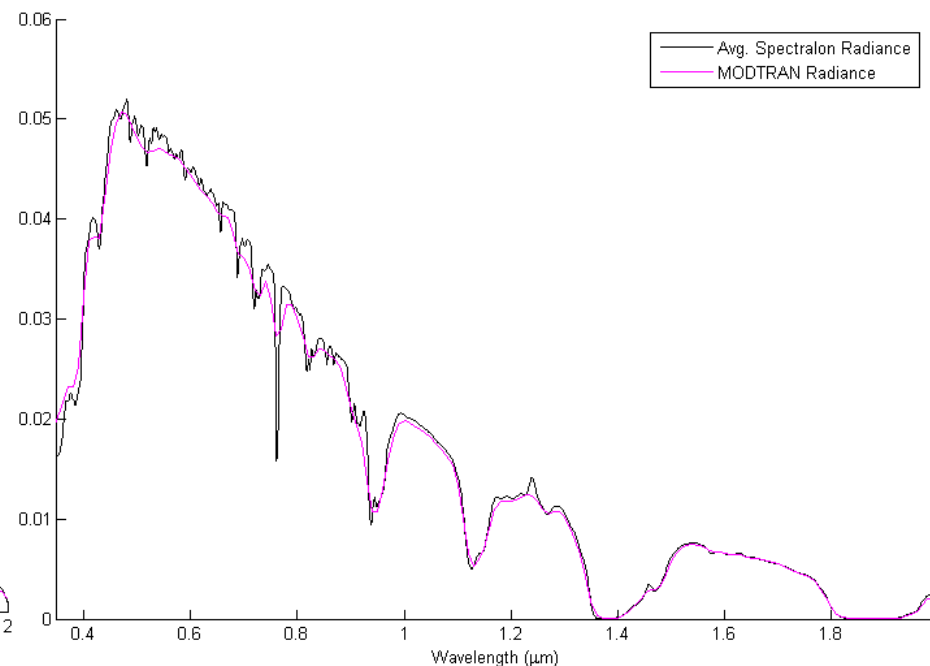
Radiative Transfer Validation Example

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MODTRAN Radiance vs. Average Spectralon Radiance from ASD

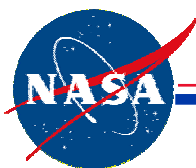


Background Reflectance Set Equal to Target Reflectance



Background Reflectance Selected by Average Region of Interest Reflectance

Adjacency as well as other radiative transfer modeling are validated

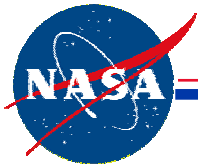


Third-generation Reflectance-based Vicarious Calibration

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	Measurements for Radiative Transfer Modeling							
	Target Reflectance	Background Reflectance	Aerosol Optical Depth	Molecular Scattering Optical Depth	Aerosol Asymmetry Factor	H ₂ O	O ₃	Radiative Transfer Validation
ASR Sun Photometer			X	X		X	X	
MFRSR Sun Photometer			X	X	X	X	X	
Radiometrically Calibrated ASD, Calibrated Panel & Shadowing (Alt. Sun Photometer)	X		X	X	X	X	X	X
Reflectance Targets		X Empirical Line Method						
Satellite H ₂ O & O ₃						X	X	

Radiometrically calibrated spectroradiometer total and diffuse panel radiance measurements allows for sun photometer and radiative transfer validation



Sun Photometer Measurements

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- Ground-level irradiance
 - Direct Normal (e.g., Automated Solar Radiometer (ASR))
 - Total, Diffuse, and derived Normal (e.g., Multifilter Rotating Shadowband Radiometers)
- Solar atmospheric transmission
 - Optical depth
 - Note: TOA radiance estimates are very sensitive to atmospheric transmission measurements
- Most sun photometers support measurements in several bands to separate key molecular and aerosol scattering and absorption bands



Traditional Sun Photometers

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**University of Arizona
Reagan ASR¹**

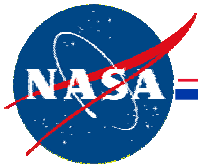
- 10 narrow bands
- 10 nm bandwidth
- Direct solar irradiance



**Multifilter Rotating
Shadowband Radiometer
(MFRSR)**

- 6 narrow bands
- 10 nm bandwidth
- Total and diffuse solar irradiance

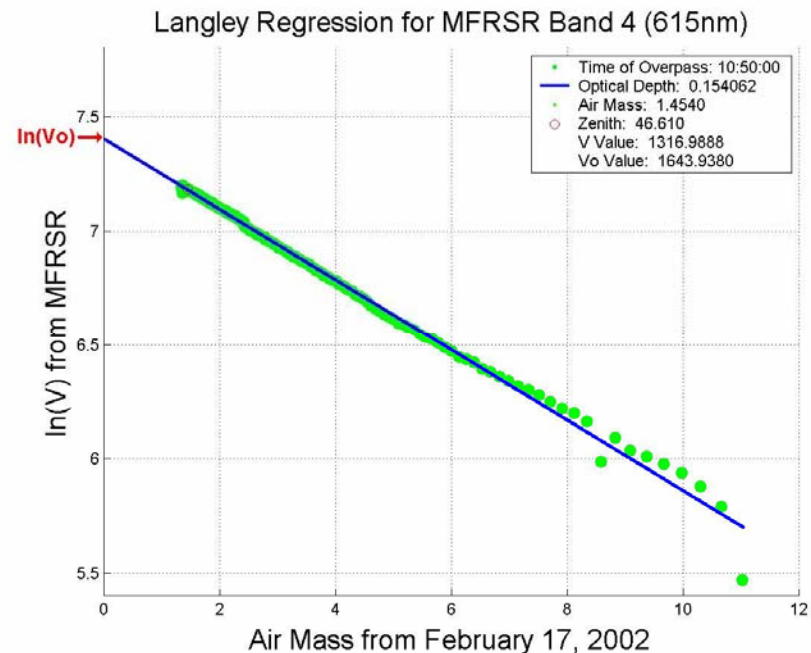
¹ University of Arizona, 2005. *Automated Solar Radiometer*. Optical Sciences Center, Remote Sensing Group: Field Equipment – Solar Radiometers. April 25. http://www.optics.arizona.edu/rsg/menu_items/resources/fld-eq.htm (accessed March 4, 2006).

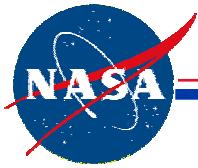


Traditional In-field Calibration of Sun Photometers

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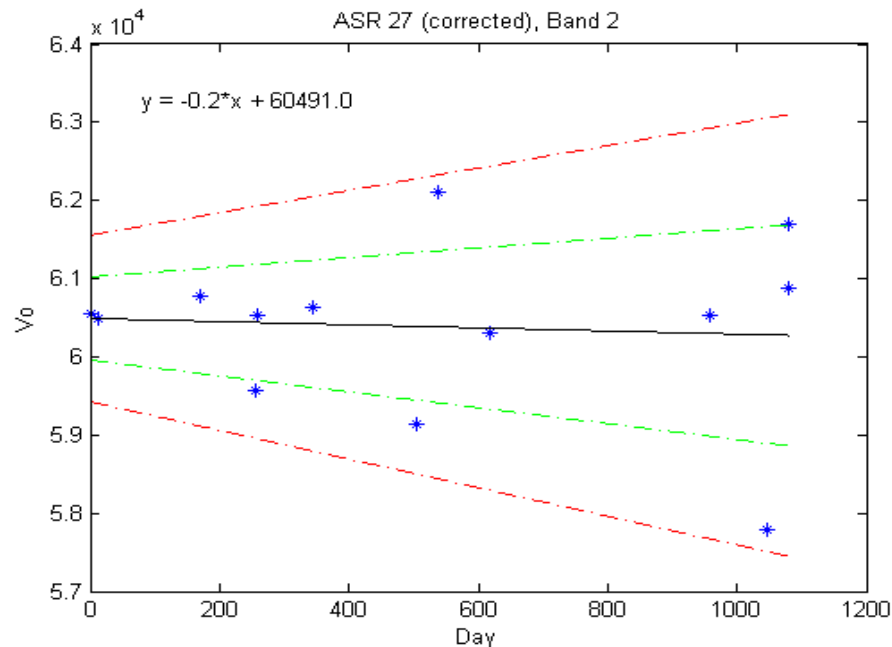
- Langley data points are in instrument units that correspond to irradiance
- TOA irradiance (V_o , E_o) values for each channel are derived from extrapolation to zero airmass
- Historical V_o values are tracked over time to verify calibration stability
- TOA irradiance varies minimally throughout the year after Sun-Earth distance correction, giving a near constant for comparison



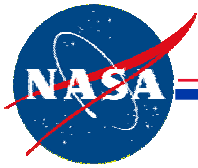


Traditional In-field Calibration of Sun Photometers (cont.)

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- Langley plot calibration requires many clear days with stationary atmospheres
 - Not practical in many locations
 - 5% or more errors in transmission are quite possible
- Built-in irradiance source or laboratory irradiance calibration could improve accuracy in areas where stationary atmospheres are difficult to achieve



Shadow Band Sun Photometers

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Total irradiance is equal to the sum of the direct component and the diffuse component

$$E_{total} = E_{direct} + E_{diffuse}$$

The direct component of irradiance can be written in the following terms:

Extraterrestrial irradiance (E_0)

Atmospheric optical thickness (τ)

Relative air mass (m)

$$E_{total} = E_0 e^{-\tau_0 m} \cos(\theta) + E_{diffuse}$$

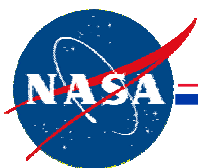
Solving for τ

$$\tau_0 = \frac{\ln(E_0) - \ln(E_{direct})}{m}$$

Diffuse-to-global ratio (D2G) used to bound molecular and aerosol scattering properties is defined as:

$$E_{diffuse} / E_{total}$$





Alternative Sun Photometer Implementation

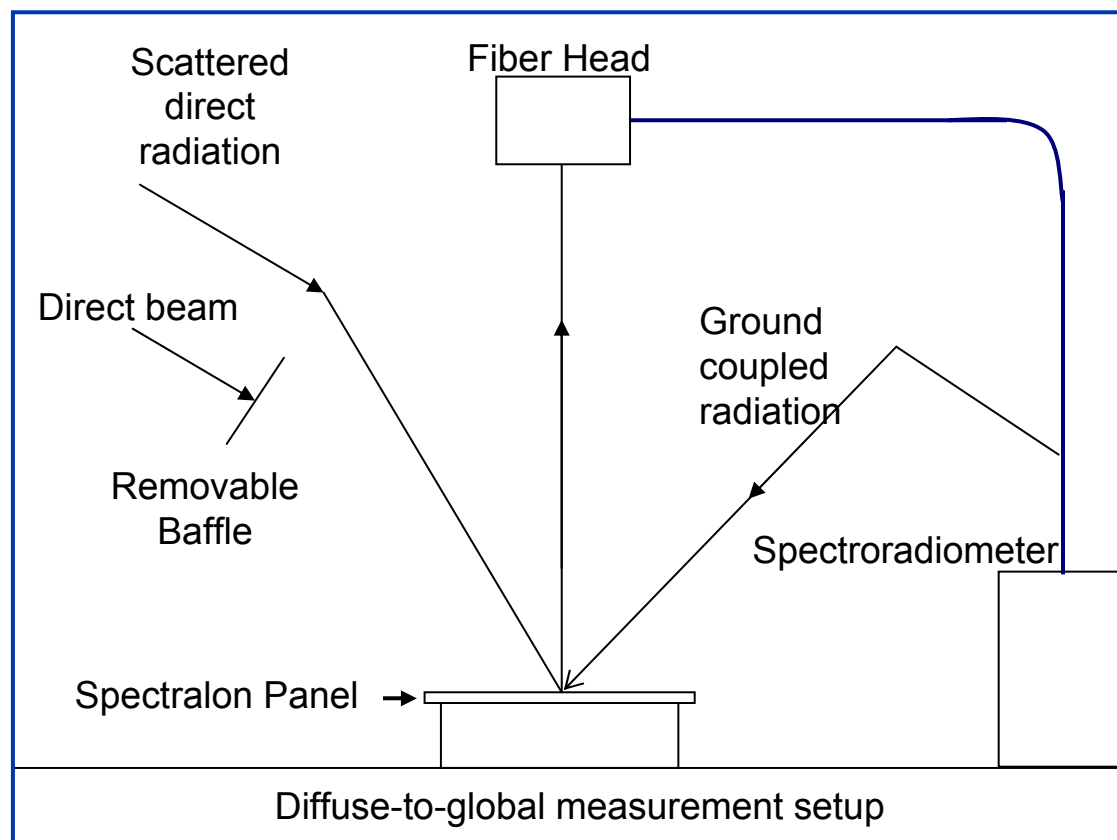
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Spectralon panel can be considered to be an irradiance-to-radiance converter if the spectroradiometer is radiometrically calibrated

$$L_{direct} = L_{total} - L_{diffuse}$$

Knowing the reflectance factor ρ as a function of zenith angle and azimuth angle

$$E_{direct} = \frac{\pi L_{direct}}{\rho \cos(\theta)}$$



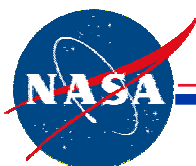


Test Case Evaluation Example

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Alternative Sun photometer data (tau) obtained using radiometrically calibrated ASD and Spectralon panel vs. traditional sun photometer (ASR) data

	SSC 1/10/04 - 16:33 GMT			
Band	ASR 27 Generated	ASD Generated	Difference ASR-ASD	Percent Difference 1 - (ASD/ASR)
380 nm	0.588	0.5982	-0.010	-1.74%
400 nm	0.495	0.4852	0.010	1.99%
440 nm	0.366	0.3216	0.044	12.14%
520 nm	0.224	0.1988	0.025	11.25%
610 nm	0.161	0.1563	0.005	2.91%
670 nm	0.108	0.1002	0.008	7.26%
780 nm	0.07	0.0691	0.001	1.33%
870 nm	0.049	0.0508	-0.002	-3.58%
		RMS 1:8	0.019	



Comparison Between Traditional and Alternative Sun Photometers TOA Radiance Prediction

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TOA radiance values for selected targets on two days. Radiance values generated with prototypical alternative sun photometer optical depth are compared to radiance values generated with the traditional method.

Date	Original Vis/ IHAZE	New Vis/ IHAZE	Targets	Bands	Original Radiance	New Radiance	Percent Difference
1/10/04	119 / 1	184 / 1	52%	Blue	151.83	153.10	-0.84 %
				Green	143.80	145.33	-1.06 %
				Red	127.23	128.65	-1.12 %
				NIR	90.845	91.688	-0.93 %
			34%	Blue	108.04	107.29	0.69 %
				Green	97.263	96.883	0.39 %
				Red	81.465	81.362	0.13 %
				NIR	55.754	55.710	0.08 %
			22%	Blue	88.622	86.982	1.85 %
				Green	76.680	75.452	1.60 %
				Red	60.965	60.174	1.30 %
				NIR	39.454	38.998	1.16 %
			3.5%	Blue	39.209	38.418	2.02 %
				Green	27.305	26.649	2.40 %
				Red	16.809	16.322	2.90 %
				NIR	9.5891	9.2478	3.56 %
4/27/05	166 / 6	84 / 6	BL	Green	40.732	41.179	-1.10 %
				Red	20.992	21.554	-2.68 %
				NIR	132.03	130.32	1.30 %
				SWIR	11.251	11.314	-0.56 %
			DG	Green	162.37	161.79	0.36 %
				Red	183.29	182.68	0.33 %
				NIR	143.02	143.70	-0.48 %
				SWIR	40.295	40.198	0.24 %
			Perk	Green	179.29	175.62	2.05 %
				Red	195.10	191.54	1.82 %
				NIR	153.98	151.47	1.63 %
				SWIR	39.088	38.477	1.56 %

Differences in TOA radiance between the two methods are negligible in most cases



Alternative Sun Photometer Summary

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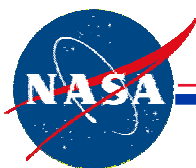
- Differences between the alternative and traditional Sun photometer data (tau, D2G) are relatively small in most cases
 - Additional analysis shows that in certain cases, the prototype may produce more accurate measurements than a traditional method in a Stennis-like environment for lack of sufficient Langley plots
 - Improves confidence in all Sun photometer measurements
- Utilizes existing commonly used vicarious calibration equipment (Spectralon panel and radiometrically calibrated spectroradiometer)
- The need for early deployment to catch many sunrises and sunsets can be minimized
- Current configuration takes hyperspectral measurements
 - Current processing uses spectral synthesis to generate bands for either MFRSR or ASR
- Spectroradiometer calibration critical to success
 - High-quality, in-field calibration could be extremely beneficial



Desired In-field Radiometric Calibration Source

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- Radiance level comparable to sea-level solar radiance values off terrestrial targets over the solar reflective region
- Radiometric stability equal to or better than 1%
- Spectrally stable
- Capable of operating over a wide temperature range (10–40 °C)
- Spatially uniform light field over at least a 25 mm diameter aperture
- Capable of operating for a continuous period of 8 hours without a line source
- Single-person portable

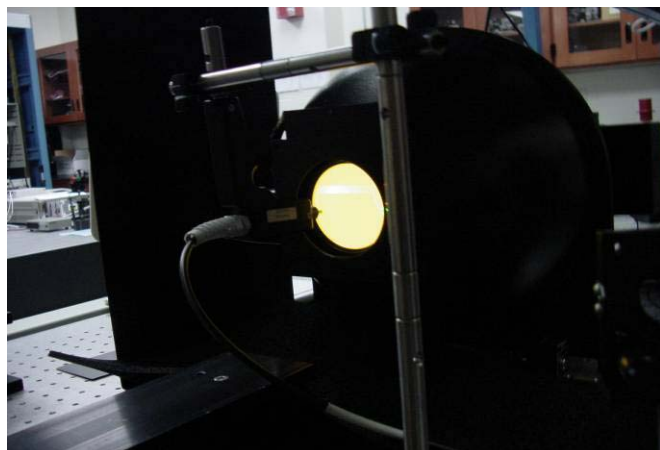


Typical Laboratory Radiometric Sources

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Radiance sources:

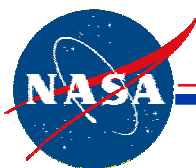
- 1) Integrating spheres
(not easily field
deployable or reliable)



- 2) Spectralon panels with
traditional Tungsten-Halogen
lamps (irradiance source)



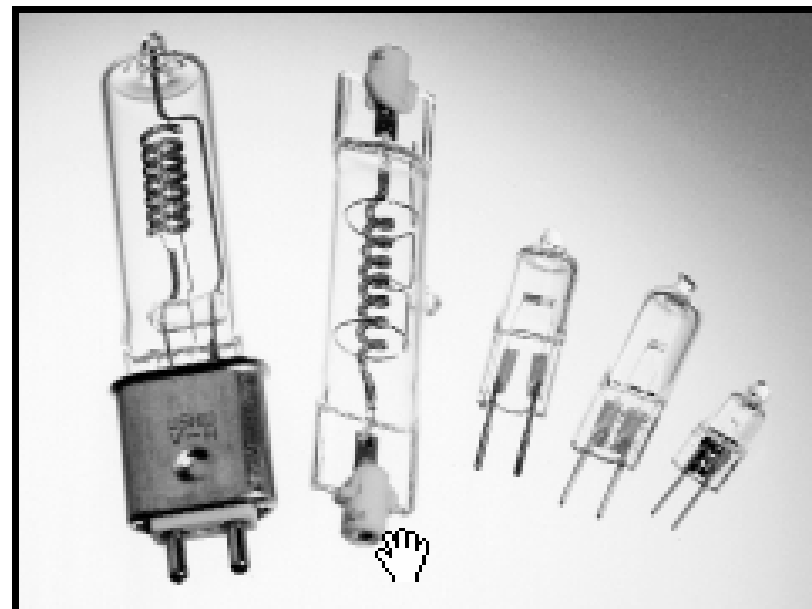
New Approach Needed for Field

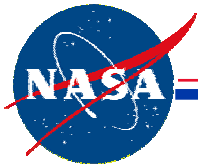


Traditional Calibration Source: Tungsten-Halogen Lamps

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- Advantages
 - Smooth spectral curve
 - Stable output
- Disadvantages
 - Expensive calibration (\$12,000 at NIST)
 - Short valid calibration period (fewer than 100 hours)
 - Low energy efficiency
 - Filament non-uniformity
 - Delicate
 - Large power requirements

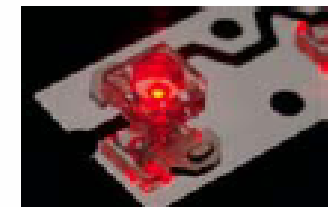
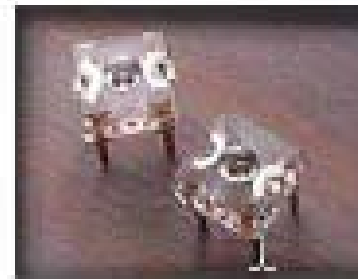


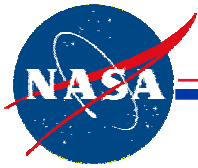


New Calibration Approach: High-Intensity LEDs

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- Advantages
 - Extreme long life 50–100 thousands of hours to 50% of initial output
 - Inexpensive
 - Reduced maintenance costs
 - Energy efficient
 - Small footprint
 - Solid state (no filament to break)
 - No heat or UV in light beam
 - Low voltage DC operation
- Disadvantages
 - Narrow spectrum (white phosphors help; sometimes an advantage)

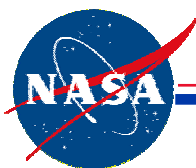




LED-based Approach

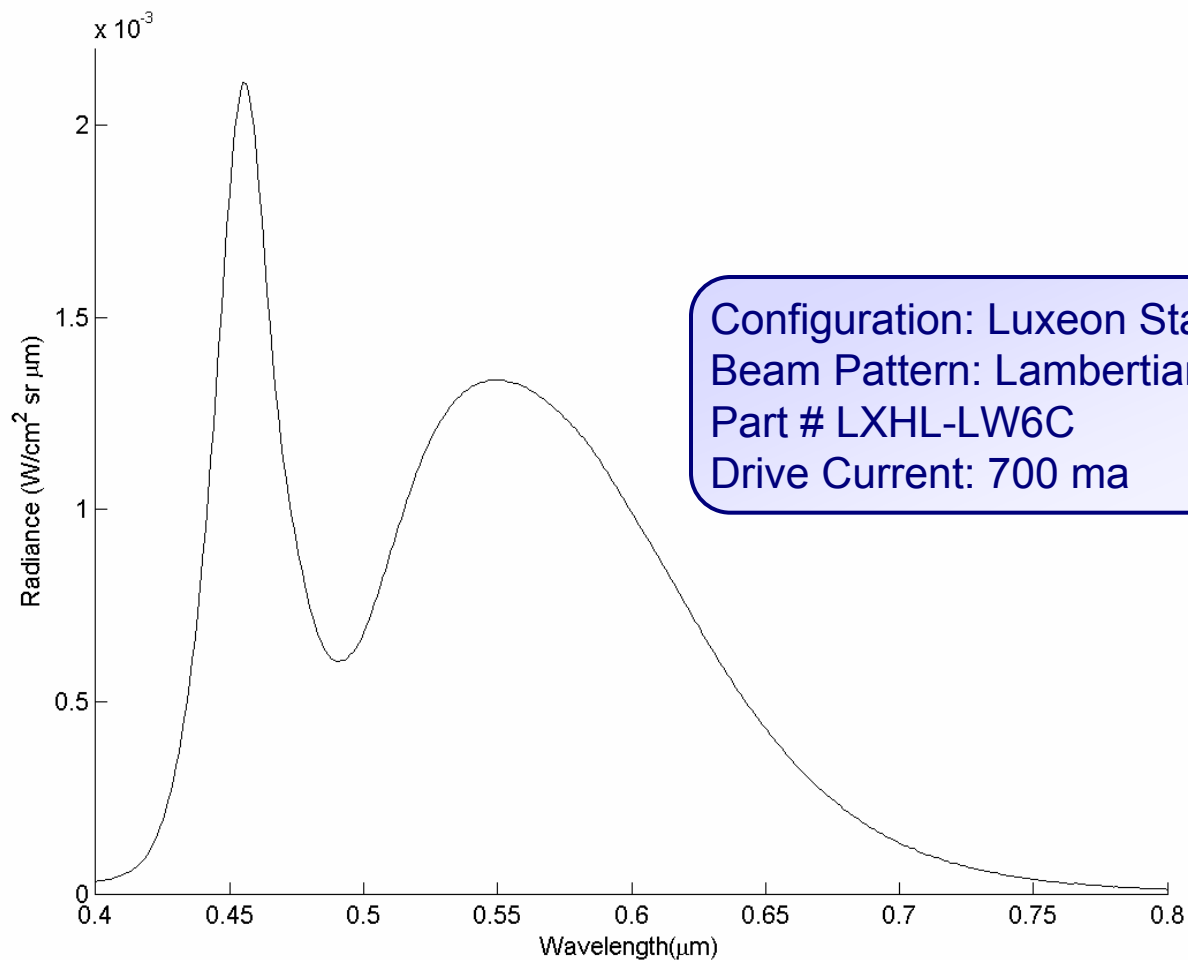
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- Exploit recent developments in high-power LED sources
- Utilize integrating sphere to create uniform light field
- Use light-stabilization control to achieve radiometric stability
- Test and characterize system with environmental chamber and independent spectroradiometer



Luxeon V DS40 White LED Radiance

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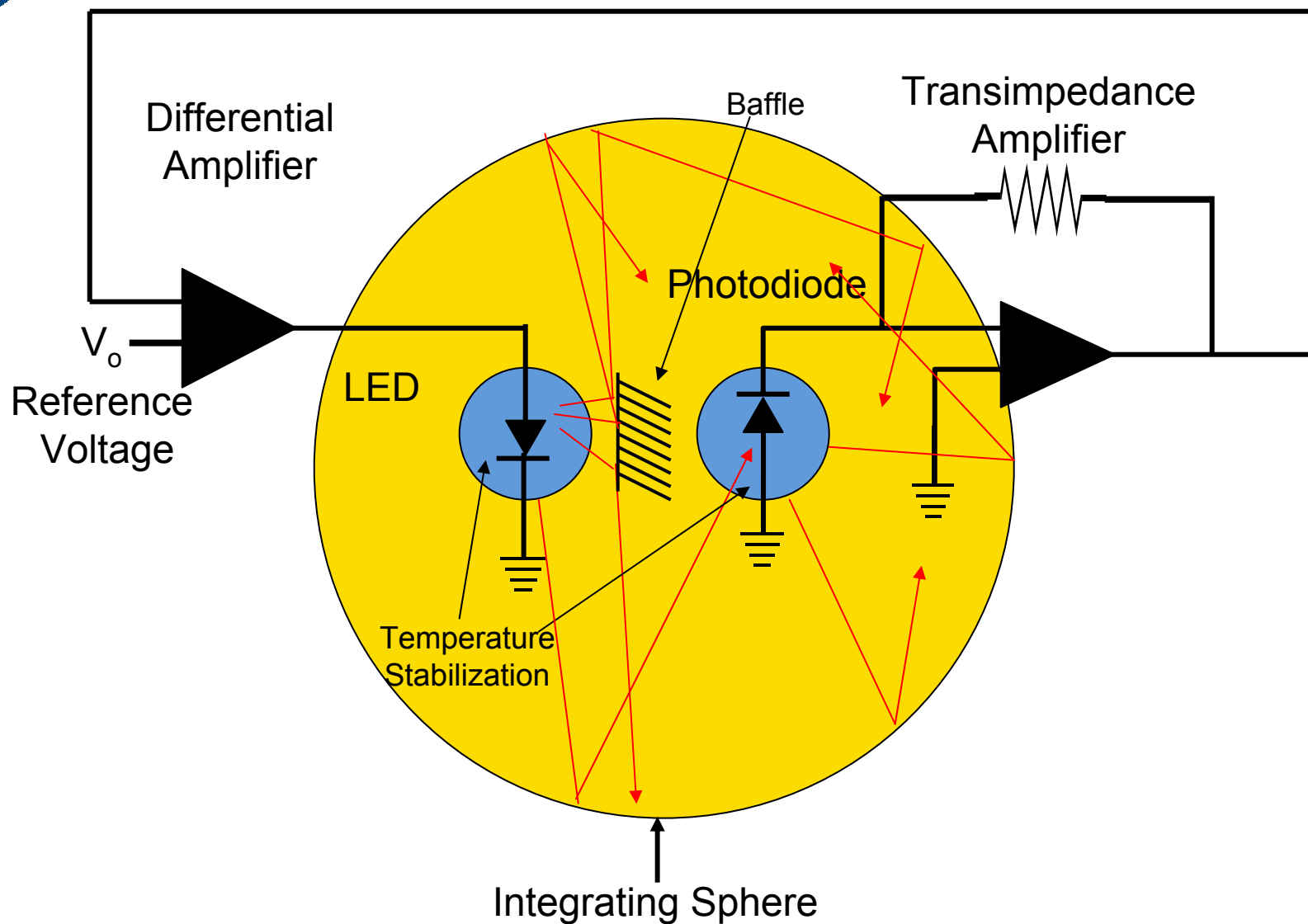
Configuration: Luxeon Star
Beam Pattern: Lambertian
Part # LXHL-LW6C
Drive Current: 700 ma

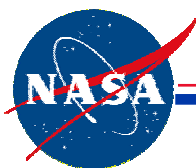
White light LEDs use blue LED pumped phosphor



LED Light-Stabilization Approach

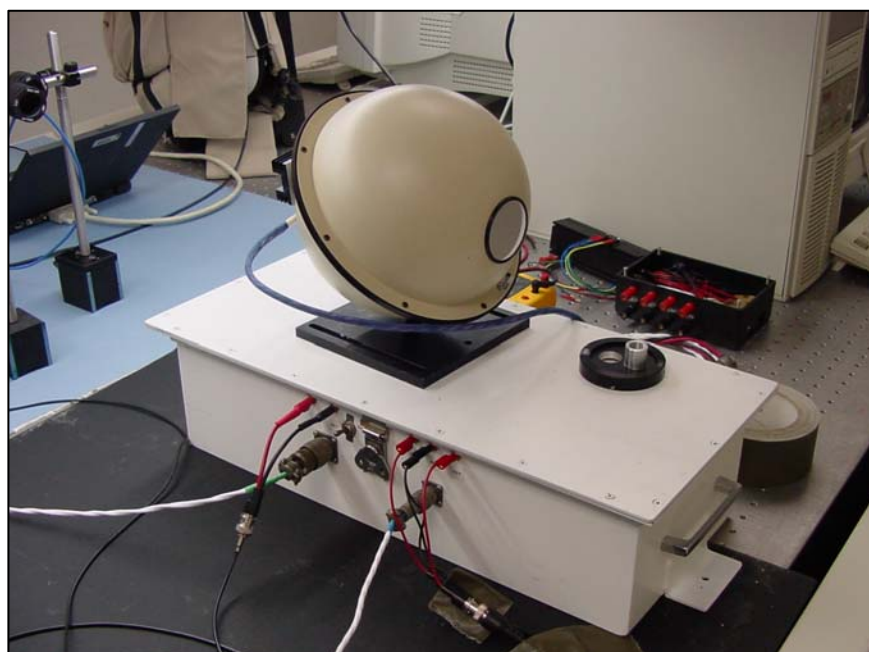
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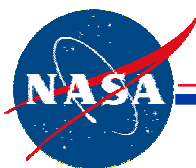
LED-based Radiance Source

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LED illuminated integrating sphere radiometric calibration source with photodiode stabilization

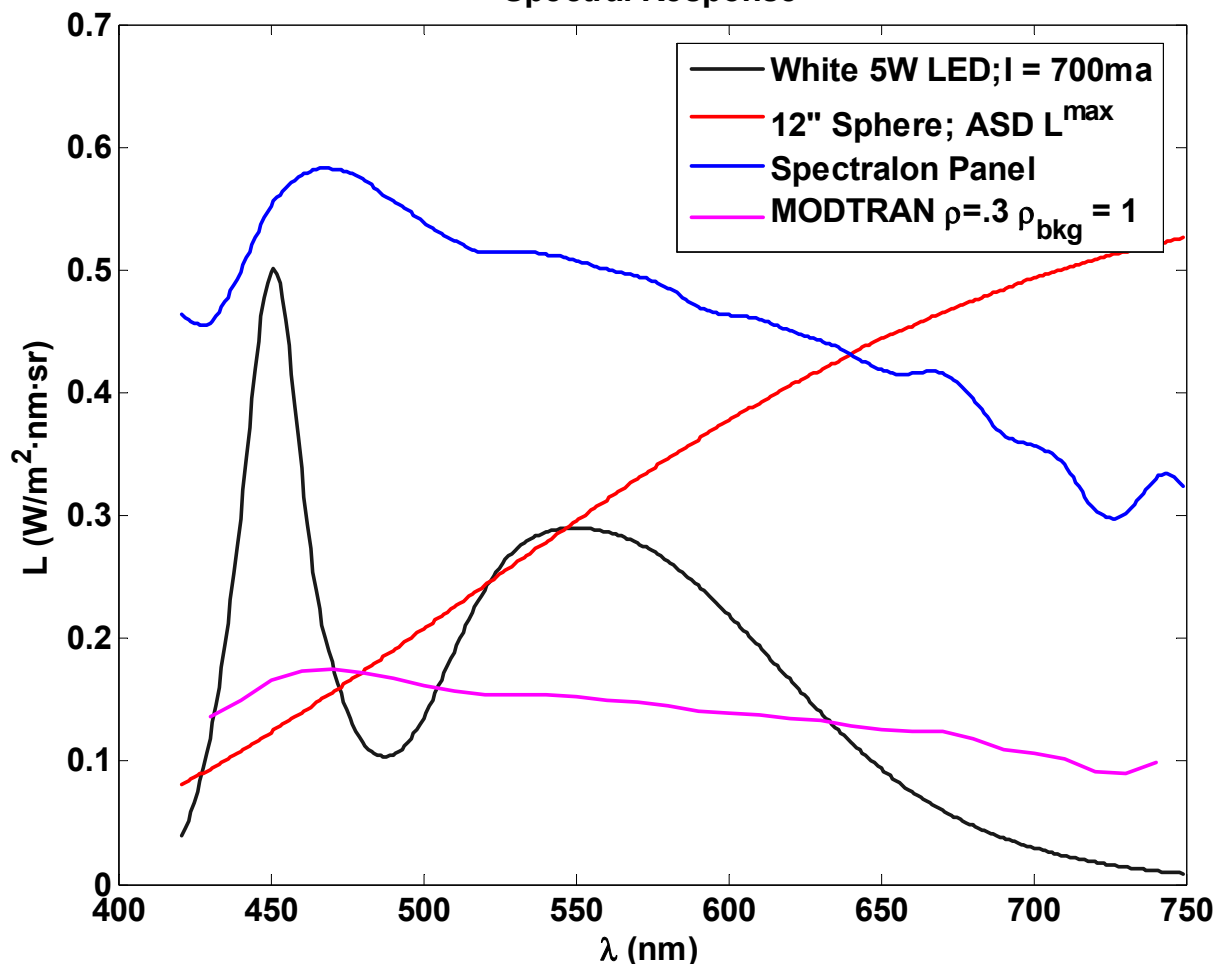
- Temperature-stabilized white light LED
 - Spectral range: 420–750 nm
 - Other LEDs would increase the spectral range
- Temperature-stabilized photodiode and feedback loop stabilize integrating sphere radiance level
- Daily lab drift <0.2%
- Short term drift <0.5% over temperature range 10–40 °C and over large spectral range



Comparison of LED Integrating Sphere With Traditional Sources

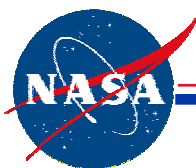
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Spectral Response



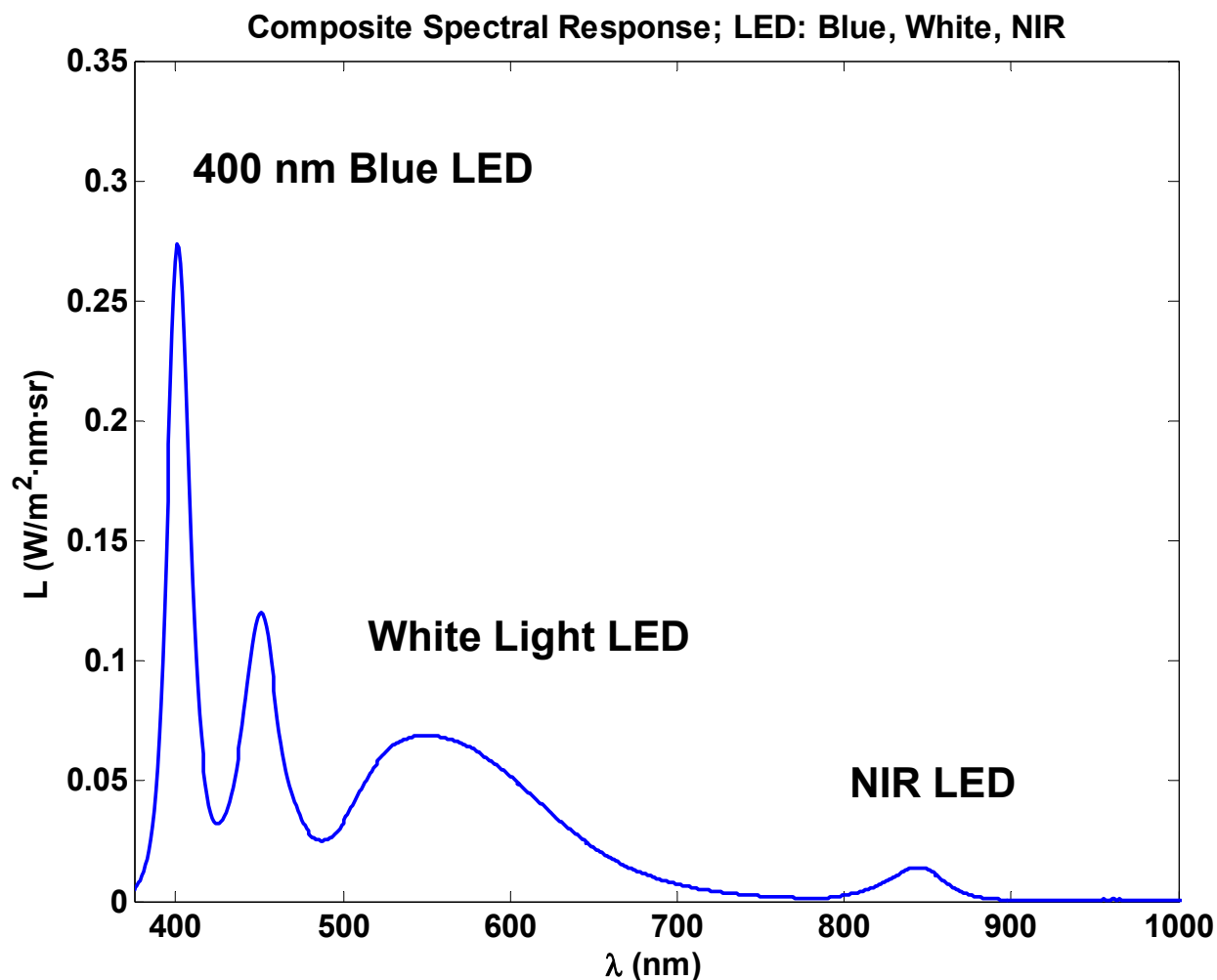
White light LED source in 8" diameter sphere produces radiance levels comparable to brightly illuminated scenes in the visible

- MODTRAN calculations for 30° solar zenith, mid-latitude summer atmosphere, 23 km visibility and rural aerosol
- TOA radiance levels calculated for 30% reflectance targets and 1 m above a Spectralon panel
- 12" sphere data for 3200 K tungsten lamp

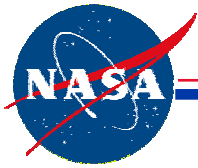


LED Spectral Synthesis

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*Exploring the use of NIR and SWIR LEDs:
additional discrete narrowband LEDs extend spectral range*



Summary and Comments

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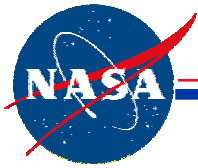
- Autonomous Visible to SWIR ground-based vicarious Cal/Val will be an essential Cal/Val component with such a large number of systems
- Radiometrically calibrated spectroradiometers can improve confidence in current ground truth data
 - Validation of radiometric modeling
 - Validation or replacement of traditional Sun photometer measurements
 - Should enable significant reduction and operation of deployed equipment, such as equipment used in traditional Sun photometer approaches



Summary and Comments (cont.)

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- Simple field-portable white light LED calibration source shows promise for visible range (420–750 nm)
 - Prototype demonstrated $<0.5\%$ drift over 10-40 °C temperature range
 - Additional complexity (more LEDs) will be necessary for extending spectral range into the NIR and SWIR
 - LED long lifetimes should produce at least several hundreds of hours or more stability, minimizing need for expensive calibrations and supporting long-duration field campaigns
 - Enabling technology for developing autonomous sites



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